




REVIEW

Diverse state-level marine aquaculture policy in the United States: Opportunities and barriers for industry development

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Funding information

This work was supported by NOAA Sea Grant NA19OAR4170346 to HEF, SEL, RRG, LDG and KDT and NSF grant 1759559 to SEL, RRG and EOR.

Abstract

Marine aquaculture (mariculture) plays a relatively small role in the United States' domestic seafood production, despite considerable scope for industry development and high volumes of imported farmed seafood resulting in a significant trade deficit. Currently, most mariculture in the United States occurs in nearshore waters or land-based tanks and is regulated and guided using state-level policy, with a relative absence of national coordinating mechanisms to link the patchwork of state policies. There is no comprehensive evaluation showing how different state policies may be enabling or impeding mariculture development. In response, we provide the first systematic overview of state-level mariculture policy for the 23 coastal marine states in the United States. We compiled information for 16 aquaculture and mariculture policy attributes, including legislation, regulations and management characteristics, particularly those that could enable mariculture development. We found considerable heterogeneity in how states govern and regulate mariculture. As examples, 48% of states have an aquaculture development act, 35% have spatial zoning specifically for mariculture and only 26% have a government-provided mariculture best management practices document. We examined the relationship between enabling policies and metrics of mariculture output (e.g. production value, number of farms), and while the effect of enabling policy is often equivocal, certain features stand out as important (e.g. government-provided best management practices). Overall, this policy synthesis suggests approaches that may be influential in enabling mariculture development, which could inform new state-level policies, an effective overarching federal policy in the United States, or policies in other countries seeking to support an expanded mariculture industry.

KEYWORDS

governance, leasing, management, mariculture, regulations, seafood farming

1 | INTRODUCTION

Marine aquaculture, or mariculture, is likely to play an increasingly important role in seafood production in the future, globally and in

the United States.^{1,2} Globally, the contribution of aquaculture to seafood supply has risen in recent decades, and currently makes up approximately half of seafood production for human consumption.³ Although most of that growth has come from freshwater

and land-based production, particularly freshwater pond culture in Asia,^{3,4} mariculture has strong potential for growth given significant space for expansion based on suitable environmental conditions.^{1,5,6} While the United States (U.S.) is a global leader in sustainable wild fisheries landings, its aquaculture production is relatively limited.^{3,7} Aquaculture in the United States primarily produces freshwater species; marine production makes up less than 1/5th of aquaculture production by volume (although about half by value).⁸ However, the United States has considerable potential to expand mariculture production given that it controls the second-largest exclusive economic zone globally, and this marine territory spans a broad range of ecological conditions that could support production of a diversity of farmed species.⁵

Increased mariculture production, through mariculture expansion, industry diversification or in some cases intensification, has been identified by some as an important policy goal for the United States.⁹⁻¹² One of the main motivations is that the United States is a major net importer of seafood (wild-caught and farmed)¹³ and mariculture development is seen as a way to reduce the seafood trade deficit.^{10,14} Proponents also argue that increased mariculture production has the potential to contribute to economic development, revitalize coastal communities and working waterfronts, increase the resilience of the domestic seafood system and provide ecosystem service benefits, such as improved water quality.¹⁵⁻¹⁷ Government policy, including legislation, regulations and management institutions, has frequently been highlighted as key to both advancing sustainable mariculture and impeding its development. At state and national levels in the United States, a lack of sufficient government support or enabling policies – or even restrictive and cumbersome regulatory processes – have been identified as barriers to industry expansion.^{9,18,19} Furthermore, government policies have the potential to help overcome other barriers to mariculture, including financial constraints and lack of necessary expertise, infrastructure or other key inputs.^{20,21} At the same time, well-crafted policy can help set appropriate environmental safeguards and place the industry on an environmentally, socially and economically sustainable pathway – important guardrails given that increased mariculture production is not a universally accepted goal in the United States.²²

Mariculture policy in the United States is complicated by state versus federal government jurisdiction and sometimes-overlapping authorities. Mariculture activities occurring in land-based tanks or in state waters (i.e. within 3 nautical miles from shore, with a few exceptions) falls under state government jurisdiction, and state agencies (e.g. fish and wildlife or agricultural agencies) are responsible for planning and management. Mariculture beyond state waters – in federal waters – falls under federal authority and is primarily managed by the National Oceanic and Atmospheric Administration (NOAA), although some federal statutes and regulations apply regardless of where mariculture occurs (e.g. Clean Water Act Section 404; Rivers and Harbors Act Section 10).¹⁹ Past federal aquaculture policy in the United States has largely centred on inland and freshwater production, while attempts to regulate marine aquaculture via the use of existing federal fisheries policy frameworks have failed;

this leaves mariculture seemingly overlooked in the national policy landscape. Although there have been numerous federal policy and regulatory attempts specifically to advance mariculture development in recent decades,^{10,14,23,24} comprehensive national mariculture legislation has yet to be passed. However, a focus on federal policy overshadows the potentially influential role of state policies and governance. Currently, nearly all U.S. mariculture takes place in state waters and land-based operations and, thus, is managed using a patchwork of state-level policies and legislation.

Despite the concentration of mariculture oversight at the state level, we lack a holistic understanding of the status of state mariculture regulations and policies across the United States. Additionally, the factors underlying how different state policies may enable or impede the development of the industry are unclear. However, research in other parts of the world, or for other food production sectors, has highlighted the critical role of effective policy in supporting the development of new industries and the productive output of existing industries, mariculture included.²⁰⁻²² For example, a global study looking at 16 study sites suggested that mariculture development and expansion is being hindered by non-standardized, overly complex, time-intensive and costly government administrative procedures and licensing processes.²⁵ These barriers were attributed to obstacles related to planning, management and regulations.²⁵ Research evaluating the temporal patterns of mariculture development worldwide found that the heterogeneity in country-level mariculture production trajectories is explained in part using indicators such as regulatory quality and governance effectiveness.²⁶ In another global analysis, regulatory quality and the existence of spatial planning were shown to be associated with higher volumes of mariculture production for some farmed species.²⁷ More broadly, a global analysis of agriculture productivity examining 127 countries found that better governance leads to higher agricultural outputs, even when controlling for agriculture inputs, education level and climate.²⁸ This body of work points to the importance of supportive government institutions and policies, but the specific policy mechanisms required likely vary depending on the context.

In this paper, we assess mariculture policy for all marine states in the United States ($n = 23$), categorizing and documenting various aspects of legislation, government objectives and programmes, regulations and management structures that govern mariculture, both through more general measures for aquaculture and those specifically aimed at mariculture. We focus on aspects of state government policy that we hypothesize could enable development, recognizing mariculture development as a policy objective that has been gaining prominence. Examples of potentially enabling factors include a streamlined regulatory process, clear government guidance on management practices and regulations, and established aquaculture development zones. We provide the first systematic overview of the state-level mariculture policy landscape in the United States and develop a metric of mariculture policy effectiveness (an 'enabling policy score'). We assess whether various metrics of mariculture output (e.g. sales value, number of farms) are associated with the enabling policy score or with individual policy attributes. Our synthesis yields

a diverse set of examples of state mariculture policies and regulations. Viewed in concert, this overview could be used to identify actionable pathways for an overarching federal policy or for a coordinating mechanism to link the collective patchwork of state aquaculture policies, while also providing useful case studies for states or other countries seeking to encourage mariculture development.

2 | STATE MARICULTURE POLICY IN THE UNITED STATES

2.1 | Policy synthesis

This analysis includes policy data from the 23 U.S. states with a marine coastline (referred to as 'marine states'). We define government policy broadly as including legislation, laws, rules, regulations, regulatory guidance, stated government objectives, government programmes, management structures, government partnerships and responsible government agencies. To assess aquaculture and mariculture government policy, we identified a set of attributes that we hypothesized could enable or facilitate mariculture development based on existing published research, including policy studies of mariculture in other countries (see Table 1 for rationales for inclusion and supporting literature for each attribute). For example, we included policy attributes that could support development by reducing barriers for permit and lease applicants, such as a streamlined regulatory process, clear government guidance on management practices and regulations, and established aquaculture development or enterprise zones. We also focused on attributes for which we could obtain consistent information across states. We collected information related to aquaculture broadly, which includes the cultivation of all aquatic species (freshwater and marine), but also included information that was specific to mariculture. While more general aquaculture policies and regulations are often applied to marine operations and thus are relevant to our analysis, we hypothesized that mariculture-specific regulations might be more influential in supporting the development of marine aquaculture given the unique issues and challenges of farming in the marine environment. For example, the nearshore and open-water environment is often considered to be public property and thus requires different types of leasing and zoning regulations than may be needed for farming operations on land. We acknowledge that definitions of mariculture can vary widely across states, and, as such, we did not apply a unifying definition in our assessment of mariculture-specific policies. Rather, we followed the definition of mariculture set forth by each individual state and evaluated their respective policies accordingly.

Our selection and analysis of policy attributes was informed using various governance theories that are commonly applied to understanding coastal systems.²⁹ Mariculture governance in the United States can be described as a polycentric system, whereby multiple decision-making agencies have created a web of decentralized and often overlapping policies and legislation that oversee the development and management of the industry.^{30,31} Thus, we hypothesized

that there might be multiple ways to achieve an enabling policy environment and selected a range of attributes to capture such diversity and complexity, while also identifying attributes that could operate from different government agencies or management structures. Our analysis was also informed by interactive governance theory, which focuses on the 'fit' between the governance system and the system being governed and whether governance is meeting the necessary challenges.^{32,33} Our focus on potential enabling factors applies this frame, attempting to identify aspects of the existing mariculture governance system that 'fit' current industry dynamics and facilitate development, such as a more streamlined permitting process or clear government-endorsed best management practices. Our assessment of each attribute attempted to determine whether existing policies create an enabling environment, paralleling similar interactive governance theory assessments conducted by others for fisheries and aquaculture.^{32,34,35}

For each marine state, we evaluated the policy attributes ($n = 16$) using binary responses (yes or no) based on whether the state currently has that attribute (i.e. existence of a particular policy, law, regulation or practice). These attributes included 11 hypothesized to be *enabling* and five that are relevant to understanding the current mariculture policy landscape (e.g. whether the same state agency oversees freshwater and marine aquaculture; Table 1), but for which our expectations were less clear regarding their enabling status. We compiled information using published literature and reports, law and policy documents, and government websites (Table S1) and searched for this information using Google, Nexis Uni and a detailed examination of government websites for the agency responsible for marine aquaculture planning and management. Four team members divided up the states to compile information and code attributes, and then a single individual verified that the information was coded consistently across attributes and states. We also identified at least one expert for each state, often someone directly involved in aquaculture management or policy for the state or a state Sea Grant aquaculture extension specialist, to assist with the validation of that state's information.

We found considerable heterogeneity among states for the types of enabling policies that are in place (Table 2). The most common attribute was leasing regulations for marine aquaculture (91% of states), and the least common was government-provided best management practices for aquaculture (26%). Only about half of states (48%) had an aquaculture development act or comprehensive legislation intended to formalize and support aquaculture development, but most of the states lacking this attribute (9 out of 12) did have some form of legislation that is supportive of marine aquaculture, albeit that legislation is not comprehensive. We found similar heterogeneity when examining the other policy attributes that are relevant to aquaculture development but that are not clearly hypothesized to be enabling factors (Table 3). These other attributes had a range of prevalence (13–78%), with a climate change policy or initiative related to aquaculture as the least common attribute (found only in Connecticut, Massachusetts and Washington). We found that agency jurisdiction over marine aquaculture was commonly

TABLE 1 Policy attributes that are hypothesized to be enabling for mariculture development, and other attributes related to mariculture policy, including a rationale and explanation for their inclusion in our study, and supporting references

	Policy attribute	Explanation and rationale	References
Enabling policy factors	Aquaculture development act or comprehensive legislation	There is an overarching aquaculture development act or comprehensive legislation intended to support the development of one or more types of aquaculture. Comprehensive enabling legislation signals a state's intent to support aquaculture development and can simplify and/or clarify the permitting and regulatory process for farmers. This attribute does not include piecemeal regulations or statutes related to aquaculture	9,20,87,88
	<u>If yes:</u> marine aquaculture provisions	The act or legislation includes specific provisions for marine aquaculture. Although there are commonalities between freshwater and marine aquaculture, having marine provision may provide a more supportive governance climate	46,89
	<u>If no:</u> non-comprehensive marine aquaculture legislation	There is not an overarching act (or there is but it does not include marine provisions), but there is legislation that is supportive of marine aquaculture despite not being comprehensive. Any enabling legislation can provide clarity and support for marine aquaculture development. This attribute does not include legislation exclusively about leasing (see next attribute)	20,88
	Marine aquaculture leasing regulations	There is a specific regulation(s) regarding marine aquaculture leasing, including both general mariculture leasing regulations or provisions that only pertain to a specific area or specific species. Having specific regulations for leasing can provide certainty and tenure security to the industry to encourage investment	20,67,90
	Supportive aquaculture initiatives or policies	There are initiatives, policies or programmes specifically aimed at enabling aquaculture. This could include programmes designed to provide funds or loans to offset the initial costs of starting a farm or to provide training to potential farmers but does not include more general government grants for aquaculture research	18,20,26
	Aquaculture best management practices (BMPs)	There is an aquaculture best management practices document, labelled as such and provided by the government (either produced by the government or officially endorsed by the government). Such guidance can help facilitate sustainable growth and clarify expectations for aquaculture development	18,42,91
	<u>If yes:</u> marine aquaculture BMPs	The best management practices document includes specific guidance for marine aquaculture	
	Spatial zoning for marine aquaculture	The state has spatial zoning specifically for marine aquaculture, such as aquaculture enterprise zones, aquaculture opportunity zones, approved aquaculture areas or potential lease sites, either statewide or locally. Creating specific zones for aquaculture can proactively encourage development, help address conflicting uses and streamline the permitting process	9,18,25,44,45
	<u>If no:</u> comprehensive multi-use marine spatial planning	The state has a comprehensive multi-use spatial plan, although it may not specifically plan for aquaculture. Such a plan signifies a state-wide commitment and process for reducing conflict among ocean uses or management goals through zoning, spatial management measures and/or comprehensive planning	9,43,44,87
	Marine aquaculture government contact	There is an easily identifiable email address and/or phone number for inquiries regarding marine aquaculture on a government website for the state agency with oversight over marine aquaculture. This signifies that the public can easily find a contact for questions or assistance	19,20
Regulatory guidance	There is state-provided comprehensive regulatory guidance, in the form of a single document posted online or a webpage, that outlines the complete regulatory process or presents a checklist of all the steps for permitting, leasing and regulatory approval. Providing specific and detailed guidance gives certainty and clarity to prospective aquaculture developers	9,20,46	

TABLE 1 (Continued)

	Policy attribute	Explanation and rationale	References
Other policy attributes	Right-to-farm statute includes aquaculture	A state's right-to-farm law includes an aquaculture clause and/or specifies that aquaculture is included in the states' definition of agriculture. Right-to-farm laws in the US protect farmers against nuisance lawsuits filed by adjacent property owners or the public, including for noise, odours, visual clutter and dangerous structures. All states have some form of a right-to-farm law, but not all of them explicitly protect marine aquaculture farmers from possible nuisance lawsuits	40
	Illegal aquaculture or aquaculture moratoriums	Some types of aquaculture are illegal in the state or there is a moratorium on producing certain species (e.g. no finfish farming in net pens, a blanket rule against farming non-native species). Rules against farming certain types of species or using certain farming methods may constrain aquaculture development	92,93
	Same agency for freshwater and marine aquaculture	Having a single agency regulating freshwater and marine aquaculture could improve integration, coordination or knowledge transfer between the sectors. On the other hand, having a dedicated agency for marine aquaculture could provide more specialized attention or priority	27
	Same agency for marine fisheries and aquaculture	Having a single agency regulating marine fisheries and marine aquaculture could allow for better integration or coordination between the sectors. On the other hand, having a dedicated agency for marine aquaculture could provide more specialized attention or priority	49
	Aquaculture and climate change policy	There is a government policy, initiative, strategy or report focused on climate change impacts, mitigation or adaptation that includes considerations for aquaculture, thus recognizing the benefit of developing resiliency to impending change	60,94

consolidated with that of freshwater aquaculture (77%), wild fisheries (78%) or both (52%).

2.2 | Enabling policy score

To develop an enabling policy score for each state, we scored each 'yes' for an enabling policy attribute as a 1 and each 'no' as a 0, except in a few cases where an attribute was nested under another characteristic and was thus assigned 0.5 points for a 'yes' (Table 2). Specifically, if a state had a comprehensive aquaculture development act, which gave them one point, they received an additional half point if the act had specific inclusions for marine aquaculture (e.g. Alaska). If the state did not have an aquaculture development act, they received a half point if they had other statutes specifically related to marine aquaculture development (e.g. Alabama). Similarly, if a state had an aquaculture best management practices document (1 point), they received an additional half point if it specifically mentioned marine aquaculture (e.g. Florida). Lastly, a state received 1 point for having zoning for marine aquaculture (e.g. aquaculture enterprise zones). If they did not have zoning specific to marine aquaculture, they are assigned half a point if they had a multi-use marine spatial planning framework, regardless of whether it had specific provisions for mariculture (e.g. Connecticut). We then summed together points for all attributes for the 'enabling policy score'. In the absence of information about the relative importance of these

different attributes for a given state, we chose to use a simplified scoring system that assumes equal (or half) weighting of all factors. We found that states range from having none of the enabling policy attributes that we examined (New Hampshire) to the highest possible score (8, New Jersey and Florida), with an average score across all states of 4.8 (Table 2). There was no strong geographic pattern for the enabling policy score, although New Jersey, Maryland and Delaware are a cluster of high scoring states (Figure 1). This may not be surprising, as there is potential motivation for these three states to influence one another and share best practices given their adjacent jurisdiction over marine natural resources in the Delaware Bay region.

2.3 | Relationship between enabling policy and mariculture output

We compared the relationships between the enabling policy score and various individual policy attributes to a series of mariculture metrics at the state-level using data from the most recent USDA Census of Aquaculture,³⁶ with all analyses conducted in R v3.6.1.³⁷ This Census provides a snapshot of U.S. aquaculture every 5–8 years (1998, 2005, 2013 and 2018) but has varying levels of consistency and detail over time and among states and is more complete for freshwater farming.³⁸ Mariculture metrics included annual sales value of marine species (in 2018 USD), number of saltwater

TABLE 2 Enabling policy score and enabling policy attributes

State	Enabling policy score	Development act or comprehensive legislation	If yes: marine aquaculture provisions	If no: non-comprehensive legislation	Leasing regulations	Supportive initiatives or policies
Alabama	2.5	N		Y	Y	N
Alaska	6.5	Y	Y		Y	Y
California	5.5	Y	Y		Y	Y
Connecticut	5	N		Y	Y	Y
Delaware	6.5	Y	N	Y	Y	Y
Florida	8	Y	Y		Y	Y
Georgia	4.5	Y	Y		Y	Y
Hawaii	4.5	N		Y	Y	Y
Louisiana	4.5	N		Y	Y	Y
Maine	3.5	N		Y	Y	Y
Maryland	7	N		Y	Y	Y
Massachusetts	7	N		Y	Y	Y
Mississippi	3.5	Y	Y		Y	Y
New Hampshire	0	N		N	N	N
New Jersey	8	Y	Y		Y	Y
New York	4	N		N	Y	Y
North Carolina	5.5	Y	Y		Y	Y
Oregon	3.5	N		N	Y	Y
Rhode Island	6	Y	Y		Y	Y
South Carolina	3.5	Y	N	Y	Y	N
Texas	1.5	Y	N	Y	N	N
Virginia	4	N		Y	Y	N
Washington	6.5	N		Y	Y	Y
Per cent of states		48%	80%	80%	91%	78%

Note: Bold columns provide 1 point and plain columns provide 0.5 points, for a highest possible score of 8. The state column is coloured by number of farms (i.e. darker purple indicates more farms), the most reliable of the mariculture output metrics.

farms, total saltwater farm surface area (acres) and number of marine species farmed. The most complete metrics were the number of farms, taxa, farm area and sales value, in that order, but all data are likely underestimates of the true values.³⁸ For these data, we excluded rainbow trout (*Oncorhynchus mykiss*) and hybrid striped bass (*Morone* sp.) because, while both species can be grown in fresh or saltwater, nearly all current production of these species in the United States is in freshwater. For annual sales value, we used data from the other metrics (e.g. number of farms), the 2013 USDA Census of Aquaculture, and state-level reporting³⁸ to determine whether zero values were true zeros versus missing data (i.e. NAs). Most states (>75%) had some level of commercial marine aquaculture production (Table 3). Only two states reported no sales from marine aquaculture in 2018 (New York and Delaware). Four additional states did not report sales in 2018 because of confidentiality or other data-sharing restrictions; most if not all these states likely had some level of production and they reported other metrics of aquaculture output.

We examined whether enabling policy explained these four metrics of mariculture output by conducting linear regressions of the enabling policy score predicting each metric (both unstandardized

and standardized using coastline length). In general, we found that the enabling policy score was not a good predictor of mariculture output given available data (Table 4). However, we found a significant relationship between the enabling policy score and number of saltwater farms, with about 27% of the variation in farm number explained using the policy score. Number of farmed species and production sales value showed non-significant but positive associations, whereas the association with farm area was essentially flat (Figure 2). Several states with high values for one or more of the mariculture output metrics had high enabling policy scores, including Washington (enabling policy score of 6.5 out of 8 maximum), Massachusetts (7) and Florida (8). Another state with the highest policy score (New Jersey, 8) had only modest levels of mariculture output and Louisiana, a state with the third-highest mariculture sales value and highest farm area, had a medium policy score (4.5). We also standardized the mariculture output metrics using the length of a state's coastline (from <https://coast.noaa.gov/data/docs/states/shorelines.pdf>) as a simple way to account for the different amounts of coastal space available for mariculture development in each state. When accounting for coastline length, only the relationship with

Aquaculture BMPs	If yes: marine aquaculture BMPs	Zoning for marine aquaculture	If no: comprehensive multi-use MSP	Government contact	Regulatory guidance
N		N	N	N	Y
N		Y		Y	Y
N		N	N	Y	Y
N		N	Y	Y	Y
N		Y		Y	Y
Y	Y	Y		Y	Y
N		N	N	N	Y
N		N	N	Y	Y
N		N	N	Y	Y
N		N	N	Y	N
Y	Y	Y		Y	Y
Y	Y	Y		Y	Y
N		N	N	N	N
N		N	N	N	N
Y	Y	Y		Y	Y
N		Y		Y	N
N		Y		Y	N
N		N	Y	N	Y
N		N	Y	Y	Y
N		N	N	Y	N
N		N	N	N	N
Y	Y	N	N	Y	N
Y	Y	N	Y	Y	Y
26%	100%	35%	27%	74%	65%

number of species was significant, with higher policy scores associated with fewer farmed species (Table 4; Figure S1). This is perhaps not surprising given the relatively low level of mariculture development in the United States – levels at which technically adequate aquaculture locations have likely not become a constraining factor.

To examine the relationship between individual policy attributes and mariculture output, we conducted two sample *t*-tests for the three mariculture metrics with the most comprehensive state coverage (number of farmed species, number of saltwater farms and sales value), comparing the states that did and did not have individual policy attributes. We found that states that had a readily identifiable government contact for mariculture and states with supportive policies or initiatives had a higher number of farmed species and a higher number of farms (Figure 3). Additionally, government-provided best management practices for aquaculture and the existence of right-to-farm legislation that applies to aquaculture were both associated with a higher number of farms. Surprisingly, zoning for marine aquaculture was associated with lower sales value, running counter to our prediction. Finally, we had hypothesized that an aquaculture development act or comprehensive legislation to support aquaculture

development would be an important driver of mariculture output, but that was not supported using our analysis, and if anything, the presence of such an act was associated with lower mariculture output (Figure 3).

3 | UNDERSTANDING POLICIES THAT ENABLE MARICULTURE

3.1 | Enabling and not-so-enabling policies

Through this analysis of state-level mariculture policy in the United States, we identified several policy attributes that were positively associated with some metrics of mariculture output, including a clearly identifiable government contact for mariculture inquiries, supportive government policies and initiatives, government-provided best management practices for mariculture, and right-to-farm legislation that pertains to aquaculture (Figure 3). Regulations for aquaculture in the United States are highly complex, and the regulatory burden has increased over time.^{18,19} As such, it appears important to have a

TABLE 3 Other policy attributes (Table 1), coastline length and measures of marine aquaculture output (2018 USDA)

State	Right to farm statute	Illegal aquaculture or moratoriums	Same agency for freshwater and marine aquaculture	Same agency for marine fisheries and aquaculture	Climate change policy	Coastline length (km)	Number of farmed species	Number of saltwater farms	Saltwater farm area (acres)	Production sales value (USD)
Alabama	N	N	Y	Y	N	977	3	4	-	\$74,000
Alaska	Y	Y	Y	Y	N	50,506	5	38	249	\$1,724,000
California	Y	Y	Y	Y	N	5515	8	21	8354	\$57,481,000
Connecticut	N	Y	Y	N	Y	995	5	26	26,884	-
Delaware	N	Y	N	Y and N ^b	N	613	1	1	-	\$0
Florida	Y	N	Y	N	N	13,576	14	178	869	\$15,552,000
Georgia	Y	N	Y	Y	N	3772	4	3	-	-
Hawaii	Y	N	Y	N	N	1693	9	23	573	-
Louisiana	Y	N	Y	Y	N	12,426	5	30	141,584	\$58,016,000
Maine	N	N	Y	Y	N	5597	10	56	1219	\$7,271,000
Maryland	Y	N	Y	Y	N	5134	7	28	1770	\$3,651,000
Massachusetts	Y	N	Y	Y	Y	2445	8	161	693	\$25,571,000
Mississippi	Y	N	N	Y	N	578	1	-	-	-
New Hampshire	Y	Y	Y	Y	N	211	4	21	79	\$542,000
New Jersey	Y	N	Y	Y	N	2884	3	42	-	\$6,434,000
New York	Y	N	Y	Y	N	4225	6	21	2102	\$0
North Carolina	N	N	N	Y	N	5432	5	39	278	\$1,328,000
Oregon	N	N	Y	N	N	2269	7	15	676	\$19,637,000
Rhode Island	Y	Y	NA ^a	Y	N	618	4	27	286	\$5,008,000
South Carolina	N	N	Y	Y	N	4628	6	14	-	\$1,826,000
Texas	N	N	N	Y	N	5406	4	15	2092	\$19,403,000
Virginia	N	N	N	Y	N	5335	6	-	-	\$94,308,000
Washington	Y	Y	Y	N	Y	4870	14	115	15,957	\$207,236,000
Per cent of states	61%	30%	77%	78%	13%	Mean	6	42	12,729	\$27,634,842

Note: When data were not available (e.g. due to confidentiality restrictions), it is noted with '-';

^aRhode Island does not have freshwater aquaculture, so attribute is not applicable.

^bShellfish aquaculture is managed by the agency in charge of marine fisheries, but all other aquaculture is managed by a different agency.

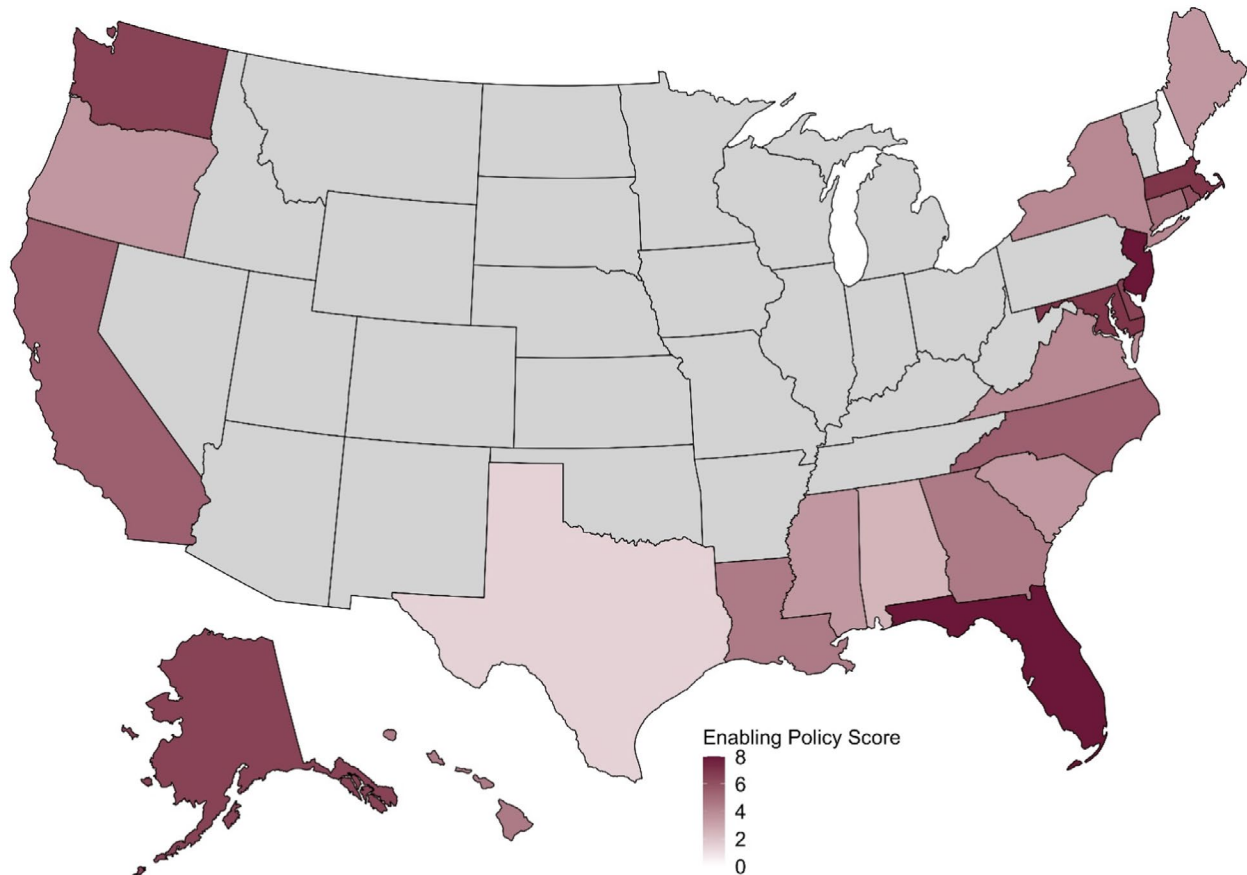


FIGURE 1 Geographic pattern of enabling policy scores presented in Table 2

TABLE 4 Linear regression results of states' enabling policy score predicting different metrics of mariculture output

Response variables	Response not standardized (Figure 2)				Response standardized per km of coastline (Figure S1)			
	N	Slope	p-value	R ²	N	Slope	p-value	R ²
Number of species	23	+	0.142	0.100	23	-	0.022*	0.226
Number of saltwater farms	21	+	0.017 [†]	0.266	21	-	0.350	0.046
Saltwater farm area (acres)	16	-	0.925	<0.001	16	+	0.979	<0.001
Production sales value (USD)	19	+	0.571	0.019	19	+	0.555	0.021

*Denotes statistically significant ($p < 0.05$).

dedicated government contact available to address questions about the permitting and regulatory process. Presence of such a contact also can indicate that a government agency has dedicated staff and resources for mariculture management. 'Right-to-farm' legislation, which protects farmers against some legal actions, such as nuisance lawsuits by neighbouring property owners related to disturbances such as noise, visual impacts or odours, have been instrumental in the United States in enabling persistence of commercial agriculture in the face of rural and suburban residential development.³⁹ While all states have right-to-farm laws, not all of them include aquaculture under the umbrella of agriculture,⁴⁰ and the role of such laws in mariculture development has not been well-studied. Given the importance of right-to-farm laws for terrestrial farming, and our finding

that states that have right-to-farm statutes applicable to aquaculture have a significantly higher number of marine farms, this issue merits additional attention.

Government-provided best management practices (BMPs) are utilized by the fewest states ($n = 6$) of all the enabling policy attributes that we assessed. Of those states that have implemented BMPs [including the USDA (2018) top two producers, Washington and Virginia], all of them include BMPs specific for marine aquaculture and all reported 2018 production sales in the millions to hundreds of millions of dollars. Of course, as is true for many if not all aspects of policy, it can be difficult to distinguish cause and effect. For example, government-provided BMPs could help spur development by providing clear guidance on acceptable practices and

efficient ways to increase productivity while removing some of the uncertainty from the permitting process,⁴¹ or higher levels of mariculture development could prompt the need for BMPs to prevent environmental degradation or other problems. BMPs also have been highlighted by the U.S. aquaculture industry as a means to develop consensus and a sort of 'soft law', with or without government involvement.⁴² While this research focused on government policy and found evidence that BMPs may be associated with industry growth, the use and impact of non-governmental BMPs on aquaculture expansion is unknown but could be influential.

Our analysis also revealed policies that do not appear to enable mariculture development, at least within the United States context. For example, mariculture zoning was associated with lower mariculture sales value, running counter to our prediction that government-identified areas for development would remove a major source of uncertainty and cost for potential farmers (i.e. site selection). In many cases, zoned areas have already been screened for some aspects of aquaculture suitability, thereby potentially reducing survey costs, feasibility assessments and conflicts with other user groups.⁴³⁻⁴⁵ Zoning can also simplify the permitting process by removing some site approval steps, which is particularly advantageous in cases where the state government has already satisfied some of the federal or state regulatory hurdles of getting approval to farm in state

waters for the zoned locations (e.g. through a programmatic general permit). As an example of zoning, Florida's Aquaculture Use Zones (AUZs) have a more streamlined process for obtaining a shellfish aquaculture lease although it is possible to apply for a lease outside of AUZs. Lastly, beyond simplifying industry entry, aggregating aquaculture operations within a zoning plan can drive the development of localized supporting infrastructure, such as roads and marinas, as well as supporting industries such as hatcheries and wholesalers.⁴⁶ However, it is possible that zoning in some cases, at least initially, is perceived as restricting development by taking locations 'off the table' or that a lack of zoning is not a roadblock to development in states with other enabling conditions. The relationship with sales value also could be complicated by the fact that some of the zoning laws are relatively new (e.g. Shellfish Aquaculture Enterprise Areas were authorized in North Carolina in 2019) or only apply to specific counties or regions within the states (e.g. Shellfish Cultivation Zones in New York were designated by Suffolk County) (Table S1).

Also contrary to our expectations, we found that comprehensive aquaculture development acts, on their own, did not appear to be necessary for enabling aquaculture development. This result may be explained by the ubiquity of piecemeal mariculture legislation in many states. A comprehensive development act can formalize and support the growth of mariculture, as can be seen in states like

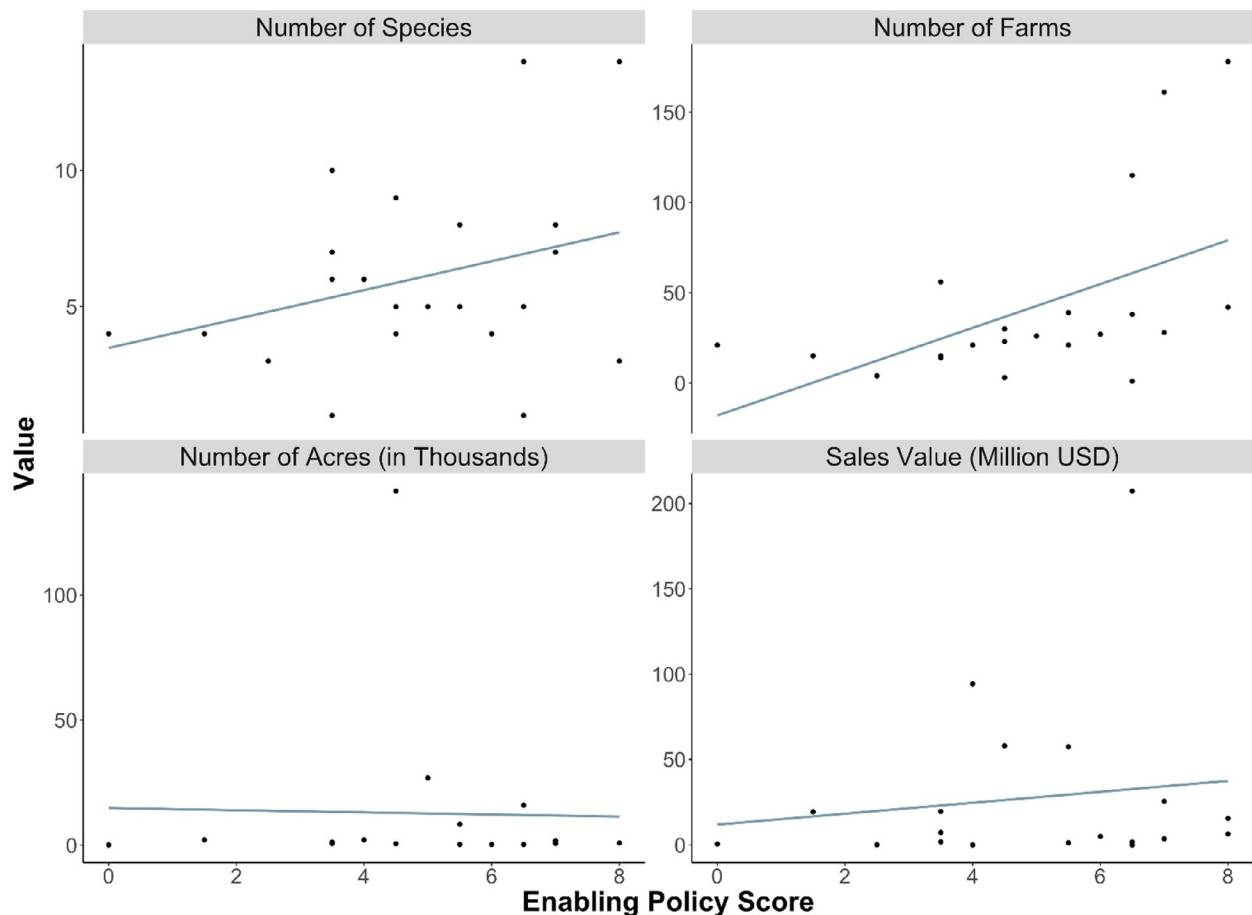


FIGURE 2 Relationships between enabling policy score and four metrics of mariculture output. Linear regression results presented in Table 4

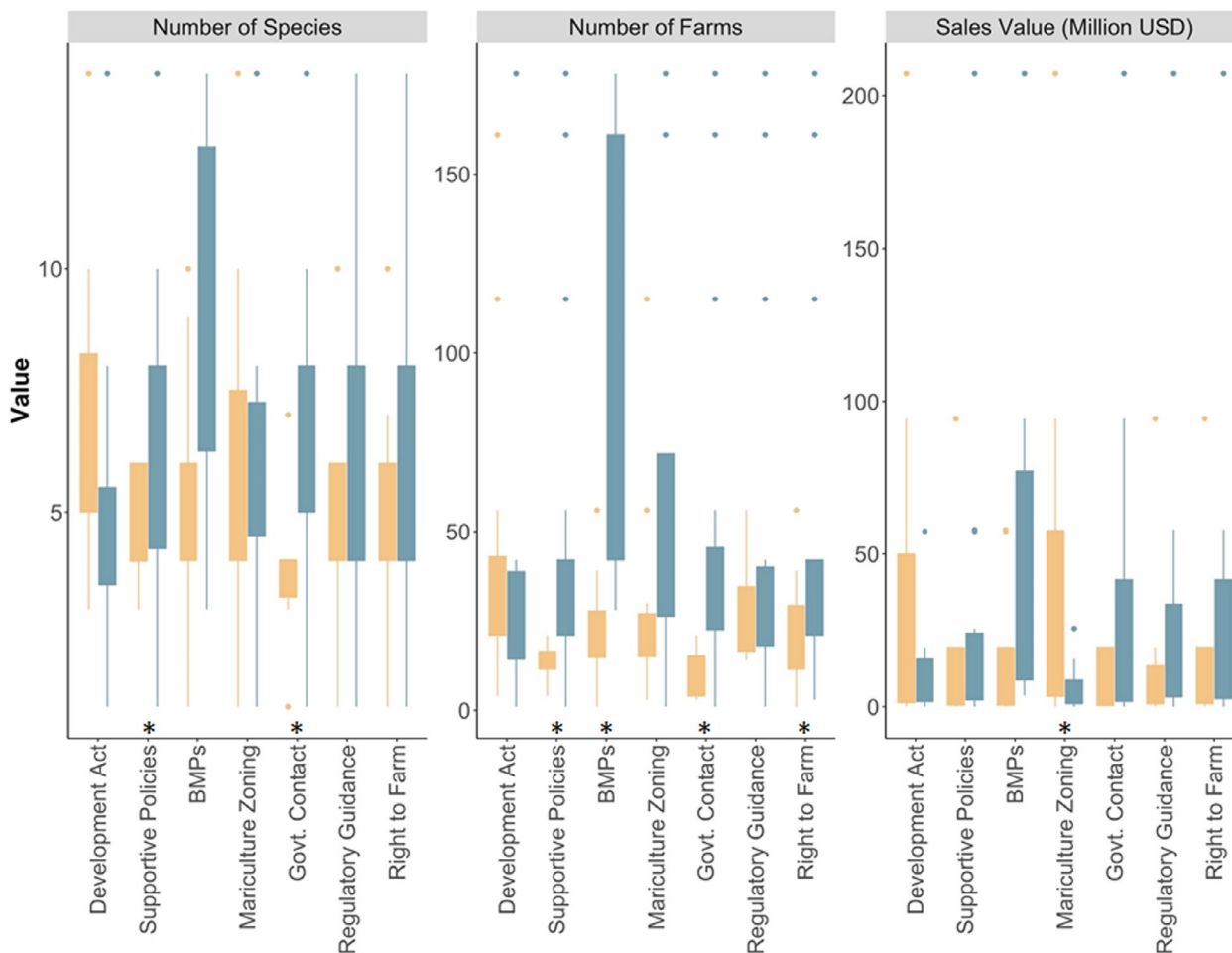


FIGURE 3 Mariculture output by the presence or absence of different policy attributes. The only significant or near significant differences (noted with '*' on the plots) were for government contact for number of species ($p = 0.020$) and number of farms ($p = 0.010$); supportive policies for number of species ($p = 0.097$) and number of farms ($p = 0.016$); best management practices (BMPs) and right to farm legislation for number of farms ($p = 0.052$ and 0.073 , respectively), and mariculture zoning for sales value ($p = 0.088$; zoning was associated with lower sales values). All other comparisons were not statistically significant ($p > 0.1$). (■) No and (■) Yes

New Jersey and Florida, but piecemeal legislation with specific aims to support development, especially when paired with targeted initiatives and collaborations, may serve a comparable function. This piecemeal approach may be commonly employed because it provides additional flexibility and can be tailored to different environments, as well as social and political contexts. Of the 12 states that did not have a comprehensive aquaculture act, nine had non-comprehensive marine aquaculture legislation and 78% of all states ($n = 18$) had initiatives, policies or programmes that support mariculture development. The only state lacking a comprehensive development act, non-comprehensive legislation and supportive initiatives or policies was New Hampshire, which had very little mariculture production. However, New Hampshire also has a very short coastline, limiting opportunities for development. Maine provides a good example of an effective piecemeal approach; the state created a non-binding but thorough Aquaculture Development Strategy alongside various legislation and other supportive initiatives. For example, Maine relies heavily on cross-sector collaborations such as the Gulf of Maine Research Institute, which is a non-profit organization that works

closely with academia and industry and receives some state funding to support the growth and sustainability of the industry. Maine also utilizes strategic initiatives, such as the Maine Aquaculture Innovation Center, which was established in 1988 by the legislature with the mission to develop sustainable aquaculture opportunities. These collaborations and initiatives likely facilitated additional informal collaborations and resulted in numerous resources and opportunities for individuals to get involved in the industry, compensating for the lack of comprehensive mariculture legislation and supporting the growth of the industry.⁴⁷ In fact, Maine's mariculture industry currently supports a range of production, from larger, often corporate, operations (>\$2 million annual sales revenue) to small-scale, locally owned operations (<\$500,000 annual sales revenue).⁴⁸

3.2 | Challenges with measuring enabling policy

There are several plausible explanations for why the enabling policy score was not a strong predictor of mariculture output (Table 4). For

one, it is a simplified index. Each primary component is weighted equally, but certain criteria likely play a more substantial role than others, and importance may vary by state. If we had better information or specific hypotheses regarding which criteria are most important, we could adjust the weightings accordingly. However, 'effective policy' is complex, multi-dimensional and highly dependent on other variables (e.g. agency capacity, political will), making it hard to quantify. It is possible that there are multiple routes or strategies to achieving enabling policy for mariculture, where in some cases a single overarching mariculture act could have a similar impact to that of multiple other policy attributes acting collectively. A state government's 'enabling attitude', for example, having staff accessible to assist potential farmers with navigating the permitting process and providing accessible resources and information to promote development, might also be more important than specific policies. Furthermore, the mariculture data are incomplete and underestimate mariculture output for all states, although the degree of underestimation varies depending on the state and mariculture metric.³⁸ The relative nascency and small magnitude of the mariculture industry in most states may hinder detection of robust relationships between policy and mariculture output. When the addition of a single farm can make a large proportional impact on state production values, noise in the data can more easily overwhelm any signal and, as an emerging sector, the industry and its governance are very dynamic. Lastly, for many policy attributes, we would expect a lag between the implementation of the attribute and any effect on mariculture output given that it takes time for policies and programmes to be fully implemented and for farms to acquire permits and become operational. It was not feasible to formally account for such lags in our analysis, but this factor alone could obscure a relationship between policy and mariculture productivity.

Another challenge is that enabling policies often have other goals beyond increasing production, such as improving social acceptance, addressing other societal goals and ensuring long-term persistence of the industry. This can complicate measuring 'success' of these policies. For example, policy can aim to provide coordination and alignment with other ocean uses and management objectives, particularly those that have the potential to conflict with mariculture such as wild fisheries. Fishers are often one of the more vocal opponents of marine aquaculture development because of concerns about market competition, preemption of fishing grounds and damage to ecosystem health or wild stocks caused by farming practices.^{49,50} We found that over 75% of states have the same agency managing fisheries and marine aquaculture, which could facilitate coordination between the two seafood sectors and alleviate potential conflicts and opposition. However, this consolidation of management also could cause the overshadowing of marine aquaculture priorities in states with robust wild fisheries or could result in rules and reporting requirements that are more appropriate to one sector being applied to the other. We found that in some states, management of shellfish farming and shellfish fishing were categorized and treated in ways that could be confusing, blurring boundaries between fishing and farming regulations. For example, in Louisiana, oyster fishers holding

a commercial fishing license and an oyster harvester license can harvest wild oysters from public or leased grounds, or can farm oysters on their leased area if they have an Alternative Oyster Culture Permit (<https://www.wlf.louisiana.gov/page/alternative-oyster-culture>).

Additionally, supportive and effective policy is often a balancing act, seeking to protect environmental and socioeconomic sustainability while also encouraging investment and entrepreneurship.²¹ Mariculture features prominently in modern blue economy discourses as a means of economic growth that will broadly benefit coastal communities.⁵¹⁻⁵³ However, efforts to identify specific policies and mechanisms by which mariculture will support communities, outside of the direct benefits of employment, are lacking.^{54,55} This 'people-policy gap' – the gap in knowledge exchange between policy makers and people who depend on aquaculture for food security, nutritional security, employment or other benefits – can create disparities and inequities in the benefits accrued from mariculture development.^{55,56} As the push for mariculture expansion continues, policy and governance can play critical roles not only in maximizing the benefits of the industry's economic growth, but also ensuring equity, social justice, nutritional security and collective well-being within the coastal communities in which mariculture takes place.^{52,54,57} This type of community-centred governance emphasizes participation and collaboration in policy and rulemaking at the local level, which is a smaller scale than our state-level analysis, but offers a valuable perspective in interpreting our findings as well as current and future expectations of the role of mariculture policy.

Finally, effective policy can support efforts to plan and prepare for future conditions to ensure the long-term sustainability and resilience of the mariculture sector. In particular, the aquaculture industry must contend with climate change. Marine aquaculture is susceptible to climate-related hazards, such as tropical cyclones, increasing ocean temperatures, ocean acidification, increased hypoxia, reduced primary productivity and sea-level rise.^{58,59} Adaptation strategies will be required to continue aquaculture growth without compromising environmental sustainability in the face of climate change,⁵⁸ and more streamlined regulatory regimes for aquaculture could help the sector be more flexible and adaptable in the face of change.⁶⁰ Government policies and regulations also can help promote forms of marine aquaculture that can directly contribute to climate change mitigation and adaptation, such as seaweed culture.⁶¹ Despite this clear need for forward-looking state policy that includes explicit climate change planning, risk mitigation and adaptation strategies for marine aquaculture, only three states (13%) had a climate change policy or strategy that included considerations for aquaculture (Table S1). Connecticut has a climate change preparedness plan that includes recommendations for strategies such as researching more disease-resistant and temperature-tolerant strains or species and improving sewage treatment infrastructure to reduce runoff during extreme rain events because of water quality impacts on shellfish farms. Massachusetts' 'act to promote climate change adaptation' includes the formation of a legislative commission to investigate the impacts of ocean acidification, including on shellfish aquaculture. Similarly, Washington has an 'integrated climate response strategy'

that includes consideration of aquaculture, particularly acidification effects on shellfish farming. Other states will likely need to follow in these footsteps to support resilient mariculture development.

3.3 | Gaps in the policy synthesis

Our enabling policy score may have been missing important attributes for enabling mariculture growth. While we attempted to document as many enabling factors as possible, we were not able to capture all factors that may be important due to a lack of comparable data across states. For example, we did not account for regulatory costs to farmers – including both the direct costs of obtaining permits and other regulatory requirements, or the indirect costs of lost farm productivity due to lengthy regulatory procedures or barriers to farm expansion or diversification to meet demand.^{42,62,63} ‘Enabling’ laws or policies may not actually facilitate industry development if the costs are too high or too uncertain. Data from the west coast of the United States have documented the substantial regulatory costs for shellfish farms, and these costs are disproportionately high for smaller operators and, thus, potential new entrants,⁶² with similar results from a study of salmonid farms throughout the United States.⁶³ Therefore, truly enabling policy may require identifying more cost-efficient and streamlined structures to achieve the same regulatory objectives.⁶⁴ Additionally, costs could be offset by government subsidies that directly or indirectly (e.g. by lowering input costs such as feeds) benefit the industry, or by government investment in mariculture infrastructure, research and development, and extension, but we did not account for such factors unless they were captured in an explicit ‘supportive initiative or policy’.

We also did not account for differences in marine tenure or ownership rights among states. Marine property rights in the United States are complex, context-specific and often ambiguous,⁶⁵ although they are generally guided by the public trust doctrine, which holds that the government has an obligation to protect marine resources (including the water column and seabed) for the public good. Thus, private ownership of submerged lands is rare, although many states do have some privately held submerged lands. It is also common for states to allow leasing of the seabed and occasionally the water column.^{65,66} For farmers, more complete ownership rights can provide more short- and long-term security for their business, and thus states that allow greater private ownership of submerged lands could facilitate more mariculture development.^{22,67}

Lastly, we did not explicitly account for governance fragmentation or for policies directly restricting aquaculture development. Polycentric mariculture governance, whereby different government agencies have jurisdiction over mariculture or where mariculture policy and management are decentralized, could decrease the efficacy of individual enabling policies. Even if key enabling factors are in place, the lack of coordination among different agencies to implement them could also hinder their efficacy, just as coordination among governing institutions can facilitate aquaculture expansion as has been seen in Norway.⁶⁸ New policies can also fail if they do not

address underlying problems with existing policy structures. For example, ‘policy layering’ whereby new elements are added to existing institutions and structures, can prevent more fundamental change or more integrated management.⁶⁹ Furthermore, while we attempted to focus on policy attributes that we hypothesized could support development and expansion, regulations regarding natural resource use in the United States often focus on environmental protection, and thus mariculture policy could aim to limit development. In a global empirical analysis of aquaculture production (including freshwater and marine production), it was found that stringent environmental regulations were significantly and negatively associated with aquaculture growth.⁷⁰ In states like California, strict environmental regulations are often seen as a barrier to coastal and ocean development, and the state has agencies that are legislatively charged with protecting ocean ecosystems and marine-protected areas that prohibit mariculture. Similarly, we did not account for policy that seeks to limit or deprioritize mariculture in favour of other ocean uses or management objectives that may be at odds with mariculture expansion, such as recreational or commercial fisheries, shipping, oil and gas extraction, water quality and species and habitat protections.

4 | LOOKING BEYOND GOVERNMENT MARICULTURE POLICY

Another reason for the weak relationship that we found between mariculture policy and mariculture output is that numerous other factors besides government mariculture policy influence development patterns. For one, the policies that impact development may not always be specific to aquaculture, and instead could reflect much broader approaches to regulating trade, industry investment and financing, coastal development and fiscal policies.⁷¹ Furthermore, looking beyond policy altogether, factors such as the availability and quality of physical infrastructure needed for both production and market delivery, available production inputs (e.g. seed/fingerlings, feed), local demand for farmed products and supportive industry organizations and financing institutions could all be important.^{20,27,71}

Aspects of governance beyond government policy, including social movements, market-based programmes and public-private partnerships, have enabled or inhibited industry development and expansion in many parts of the world.^{72,73} Environmental non-governmental organizations have played a particularly large role in sustainable seafood governance, leading sustainability initiatives, developing production standards and shaping public attitudes about aquaculture.⁷² Private companies have also been influential, developing regulations and standards to improve aquaculture performance in the face of over- or under-regulation by governments.⁷³ Many of these efforts are market-based approaches, such as certification schemes, eco-labels and consumer guides, which attempt to motivate more sustainable aquaculture practices with market incentives.⁷³ Further, farmers have attempted to leverage collective action and social movements to reduce environment risks⁷⁴ or develop more inclusive sustainability standards along the full value chain.⁷⁵

Public attitudes towards mariculture are also important,^{18,76} and commercial mariculture has not garnered the widespread social licence to operate afforded to terrestrial agriculture or to wild fisheries in many states.^{77,78} The industry has faced opposition, particularly from conservation and fishing interest groups and coastal property owners, slowing or even blocking development in some areas.^{79,80} Thus, the availability of ocean space with both suitable mariculture production conditions and limited-to-no conflict with other established marine activities could play a role in state-level industry development.⁸¹

5 | IMPLICATIONS

This synthesis is a snapshot of state-level policies and regulations for sustainable mariculture development in the United States. It provides information from which current and future efforts to develop mariculture policies and regulations at local, state and federal levels can benefit, as well as a catalyst for more research ideas and opportunities to better understand the relationship between policy and sustainable mariculture development. This synthesis could promote coordination and learning across states and between agencies responsible for managing marine and freshwater sectors, facilitate regional or interagency cooperation and inform a federal strategy to support mariculture development. Information exchange across states is often hindered by a lack of cooperative mechanisms and incentives.¹⁹ A central repository of current policies, practices and regulations could help circumvent these hurdles. For instance, states interested in creating new mariculture policies can use the repository to explore what other states have enacted to inform their decisions and processes, as well as initiate greater knowledge transfer among states, a critical domain for building adaptive capacity into aquatic food sectors.^{82,83}

Aquaculture is a rapidly growing sector across many regions of the world, and thus the lessons learned from this analysis could be relevant for helping shape sustainable growth strategies in both marine and freshwater aquaculture and across a diversity of countries. A recent global synthesis of national mariculture policy found that many countries with growing marine aquaculture industries have some level of regulation and environmental protections, but do not have clear policy frameworks for continued growth of the sector, particularly in the offshore realm.^{22,84} As growth continues, many of these countries will be working to develop new policy to ensure sustainable growth while enabling continued industry expansion. As examples, Canada is experiencing growing motivation for national legislation to provide state support for aquaculture expansion that is environmentally sustainable and socially responsible,⁸⁵ and Australia has a National Aquaculture Strategy that identifies efficient regulatory frameworks as a top priority for encouraging industry growth.⁸⁶ While marine aquaculture was central to this research, overlap and interaction with freshwater aquaculture directly (e.g. anadromous species) and indirectly (e.g. governing agencies, markets) further highlights the value of clear planning and policies

for the sector as a whole. Thus, the enabling attributes and example policies synthesized here provide a useful resource to other nations seeking to support aquaculture development.

In addition to the implications of our synthesis in applied aquaculture settings, this work also contributes to the broader scholarship on polycentric governance, specifically within the context of marine spaces. As the ocean is not a static environment like its terrestrial counterpart, there are unique dynamics and challenges to decentralized marine governance, which drives new considerations of how polycentric systems are operationalized. Importantly, the diversity of policy approaches documented in this synthesis suggests that creating an enabling (or restrictive) policy environment for marine aquaculture can be accomplished by a variety of means. These results indicate that there is not a simple formula to encourage development; however, there are certain characteristics that do seem to be associated with more successful mariculture development.

As aquaculture for marine and freshwater species continues to expand – in the United States and around the world – policy will be an important driver of expansion patterns. Additionally, effective policy can be important for safeguarding against environmental damage, promoting production methods that will be sustainable and resilient to climate change, providing resources for management and monitoring, preventing private interests from eroding public goods and benefits, and decreasing conflicts among ocean user groups. Understanding the different policy approaches that states are using to strive for achieving these diverse objectives is useful for charting a productive and sustainable pathway for U.S. mariculture and global aquaculture more broadly.

ACKNOWLEDGEMENTS

The authors thank the Sea Grant Law Center and National Sea Grant Extension Network for help on the initial stages of this project, and aquaculture experts in each state for reviewing and providing feedback on the policy information in Table S1. This work was supported by NOAA Sea Grant NA19OAR4170346 to HEF, SEL, RRG and KT and NSF grant 1759559 to SEL, RRG and EOR.

CONFLICT OF INTEREST

HEF sits on the Technical Advisory Group for the Aquaculture Stewardship Council. KDT sits on the Standards Oversight Committee for the Global Seafood Alliance's Best Aquaculture Practices. All other authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

All data used in analyses are provided in tables within the paper. Information supporting the enabling policy score is provided in the supplementary information.

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How to cite this article: Lester SE, Gentry RR, Lemoine HR, et al. Diverse state-level marine aquaculture policy in the United States: Opportunities and barriers for industry development. *Rev Aquac.* 2021;00:1-17. <https://doi.org/10.1111/raq.12631>